Environmental Science & Technology
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Policy Analysis

Integrated Biological Risk and Cost Model Analysis Supports a Geopolitical Shift in Ballast Water Management

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Cite This: *Environ. Sci. Technol.* 2021, 55, 12791−12800

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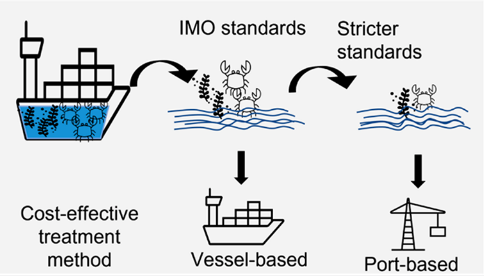
ABSTRACT: This work evaluates efficacies of plausible ballast water management strategies and standards by integrating a global species spread risk assessment with a policy cost-effectiveness analysis. Specifically, we consider species spread risks and costs of port- and vessel-based strategies under both current organism concentration standards and stricter standards proposed by California. For each scenario, we estimate species spread risks and patterns using a higher-order analysis of a global ship-borne species spread model and estimate fleet costs for vessel- and barge-based ballast water treatment systems for each standard. We find that stricter standards may reduce species spread risk by a factor of 17 globally and would greatly simplify the complex network of ship-borne species spread. The current policy of IMO standards is most cost-effectively achieved through ship-based treatment, and that any additional risk reduction will be most cost-effectively achieved by port-based (or barge-based) technologies, particularly if these are strategically implemented at the top ports within the largest clusters. Barge-based ballast water management would require a shift in governance, and we suggest that this next level of policymaking could be feasible for special areas designated by the IMO, by State or multistate authorities, or by voluntary port applications.



KEYWORDS: *aquatic invasion, risk assessment, ballast water management, network analysis, cost-effectiveness analysis, cluster analysis*

■ INTRODUCTION

Harmful aquatic organisms and pathogens (HAOPs) are major threats to ocean ecosystems and economies, and shipping is a major vector of these species worldwide.[1] The International Convention for the Control and Management of Ships' Ballast Water and Sediments (BWM Convention) was adopted in 2004, aiming to prevent, minimize, and ultimately eliminate the risk of introducing HAOPs transferred in ships' ballast water and sediments. The BWM Convention's general approach follows two widely accepted science-based guidelines for mitigating HAOP spread: prevention and vector-based management. Prevention of HAOP establishment in new areas is a more powerful and efficient management approach compared to removal of established populations, the latter which is usually logistically impossible in an open coastal environment.[2−5] Vector-based management approaches,[6] which can manage the entire assemblages of HAOP associated with ship-borne transport mechanisms, are also seen as efficient because they avoid the requirements of extensive information of the invasion history and biological traits in species-specific risk assessment.[2,7]

Although BWM Convention's general HAOP mitigation approach is well-supported by evidence, there are issues with its standards. The D-2 standards of the Convention stipulate acceptable concentrations of organisms in discharged ballast water. The standards are different for two categories of "viable organisms" and three categories of "indicator microbes". These regulations are uniform across ports, but HAOP spread risks vary at different locations.[8−11] Stricter regional regulatory standards may be needed to achieve better protection for certain ports, particularly those with high HAOP spread risk or those that serve as key hubs in the global shipping network.

Though the IMO BWM Convention incorporates principles of risk,[12] over the past decade several improvements have been made to modeling commercial ship-borne species spread risk.[3,8,11,13−15] These models adopt a stage-based framework widely used in invasion biology, whereby species transport probability (probability of being transported to a new area) and establishment probability (probability of surviving and reproducing a viable population) are estimated separately, and spread probability is conditional on both transport and establishment occurring. Most models do not attempt to estimate the third stage, invasion probability, or likelihood that a species becomes a nuisance or HAOP, as this is more subjective and difficult state to estimate at a global scale. They instead implicitly assume that invasion probability is a small but constant fraction of the spread probability. While this latter

Received: June 17, 2021
Published: September 14, 2021

https://doi.org/10.1021/acs.est.1c04009

assumption prohibits quantitative HAOP risk estimate, it can provide relative HAOP risk estimates that can rank riskiness of routes and ports and can also be used for evaluating relative risk reduction under different scenarios. This modeling framework, combined with global data sets of ship traffic[16] and port environments,[13] the U.S. National Ballast Information Clearinghouse (https://nbic.si.edu/), and numerous smaller-scale studies estimating species survival in ballast water over time, have enabled route- and port-based species spread risk assessments at global scales.[3,8,11,13,17]

The ship-borne species spread risk model used here is based on a higher-order network (HON) model and analysis of Saebi et al.[8] Previous spread analyses,[6,11,14,18] implicitly assume that ship-borne species spread in a first-order Markovian process. Under this assumption, the spread risk between two ports is only a result of direct exchange of ballast water between the two ports.[19] Ignoring the dependence on multiple past voyages of any destination port neglects carryover of species due to partial ballast water discharge introduced from prior ports.[8,20] The HON approach by Saebi et al.[8] is shown to provide more accurate risk assessment and reveal port clusters within which species spread risk is high,[8,18,20] both of which are useful for policy development and implementation.

This paper performs a risk reduction and cost-model analysis within a policy intervention context. We specifically focus on technological solutions to comply with the BWM Convention's D-2 standards, considering vessel- and barge-based methods. In general, three different treatment methods can be used: vessel-based ballast water management system (BWMS), land-based facility, and barge-based facility. The land- and barge-based method together can be called port-based method. The advantages of vessel-based BWMS includes flexibility in terms of location and timing of use. Port-based BWMS can accommodate larger and heavier BWMS, allow more time for treatment processes, and can be safer for workers, but may have infrastructure limits.[21−24] Barge-based systems provide more flexibility than the land-based but still have capacity/location limits. D-2 standards of the Convention are typically achieved with on-board BWMS. The initial purchase and installation of one BWMS can cost \$0.2 to \$ 1 million per vessel, depending on its capacity and treatment method (e.g., mechanical, physical, or chemical method).[25,26] The feasibility study of barge-based treatment systems to achieve the interim standards of California was conducted. The study shows that the capital and installation of a BWMS designed to achieve the stricter California standards is \$4 to \$10 million, and the capital and outfitting cost for one barge is \$6 to 15 million.[27] The barge-based systems require additional outfitting costs caused by ballast water transfer stations and operating costs caused by personnel to operate the stations.[27] However, the port-based facility can offer economies of scale since it is used by a number of vessels[28] and avoid the costs in BWMS retrofitting at every vessel should standards change in the future.[29,30] Considering different options, Wang and Corbett conducted a preliminary cost-effectiveness analysis (CEA) to identified that the least costly compliance technology under three policy scenarios focusing on the U.S. ports.[26] However, they simply assume one barged-based BWMS is enough at each port and did not consider ship-borne spread risk, the problem that the BWM Convention is trying to address, in its analysis.

To holistically evaluate the efficiencies of BWM approaches, this work presents an integrated analysis to move BWM policies forward with a risk-policy-economic-technology nexus. By connecting the risk-assessment modeling of Saebi et al.[8] with policy cost modeling of Wang and Corbett,[26] we produce insights regarding both environmental risk-reduction and economic cost-effectiveness. Specifically, we improve the models in three ways: (1) we use a more accurate random forest model to estimate ballast water discharge volume in both models, (2) we vary the number of needed barges and ballast water treatment system at ports in the cost model according to the historical vessel arrival records, and (3) most importantly, we evaluate efficiencies under scenarios where different numbers of ports adopt stricter regulations. The generally applied modeling enables technology-policy analysis together with risk assessment to inform whether barge-based BWM could be both risk- and cost-effective. These two dimensions represent key criteria to inform science-based policy. This analysis considers two general policy scenarios in the global context: the current IMO policy and a potentially stricter policy represented by the interim California standards, which are thus far the only alternative BWM standards that have been officially proposed.

METHODS

We evaluate HAOP risk and economic costs of barge-based and vessel-based BWM under current IMO standards and stricter standards that have been proposed by California. HAOP risk is estimated with a HON risk assessment model. Key patterns, such as intra- and intercluster HAOP spread pathways and ports linking several clusters, are reveals with clustering analysis. We further conduct an improved cost-effectiveness analysis on compliance technologies at 4257 world ports in international trade contained in Lloyd's List Intelligence (LLI) in a stepwise process under both regulatory scenarios.

The HAOP Spread Risk Assessment Model. The HON risk model integrates ship trajectories, environmental similarity (temperature and salinity), and biogeographical data of the ports.[8] The model is illustrated in Figure 1.

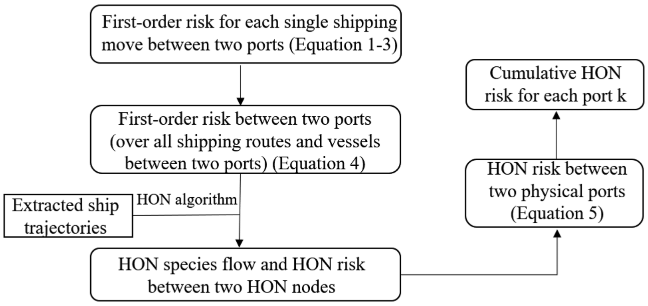


Figure 1. HAOP spread risk assessment model flowchart.

The invasion risk spread for a single shipping move (ship ν traveling from port i to port j) is the product of these three components:

$$p(\mathrm{NISspread})_{ij}^{\nu} = p(\mathrm{nonindigenous})_{ij} \times p(\mathrm{intro})_{ij}^{\nu} \times p(\mathrm{establish})_{ij} \tag{1}$$

The first item in this risk equation is the probability of being nonindigenous, which is included because we assume that HAOP are introduced to novel regions by ships and not by natural vectors. Since neighboring ecosystems are likely to share more species due to natural dispersal,[31,32] we estimate the nonindigenous probability is 0 if both origin and target ports are in the same or neighboring ecoregions, and 1 otherwise.

The second item is the relative introduction risk. This assumes that species introduction risk is related to discharge volume, but it does not quantify the exact probability of introduction per volume discharge. Even though long-term survival in tanks and possibly even reproduction may happen for some species, in general, the survivorship declines with increased voyage sailing time.[33] For each ship ν traveling from port i to port j during the time Δt_{ij}^{ν} we have

$$p(\text{intro})_{ij}^{\nu} = \rho^{\nu}(1 - e^{-\lambda D_{ij}^{\nu}})e^{-\mu \Delta t_{ij}^{\nu}} \tag{2}$$

Where D_{ij}^{ν} is ballast water discharge volume at a port, estimated with a random forest model described in the Supporting Information (SI). λ is a characteristic constant (3.22×10^{-6}),[11,17] used to scale the introduction probability. $1 - \rho^{\nu}$ is the efficacy of BWM for the voyage. We use species concentration reduction percentages to describe the efficacy[21,34−39] (refer to SI Table S2 about the reviewed data). The efficacy of is 76% of in-service BWMS (estimated with experimental results in reviewed literature), 99% of perfectly achieved IMO standards (calculated with the sampled organism concentrations in untreated water and the IMO numeric standards), and 99.9% of perfectly achieved California stricter standards.

The third item is the probability of establishment, which declines with increasing mismatch in temperature and salinity values. Although many other factors influence establishment, as outlined by Wonham et al.,[15] these factors were not included based on available data. For every pair of ports (i,j) this probability uses the temperature difference ΔT_{ij} and the salinity difference ΔS_{ij} between port i and port j as follows:

$$p(\text{establishment})_{ij} = \alpha e^{-1/2\left[\left(\frac{\Delta T_{ij}}{\delta T}\right)^2 + \left(\frac{\Delta S_{ij}}{\delta S}\right)^2\right]} \tag{3}$$

where δT and δS are the standard deviation in temperature and salinity.

The above equations estimate the risk of a single shipping move. Since many ship moves are between a port pair and may cause invasion, for every port pair i to j, we aggregate the risks over all shipping moves of all vessels to calculate pairwise first-order risks:

$$p(\text{NISspread})_{ij} = 1 - \Pi_{r,\nu}(1 - p(\text{NISspread})_{ij}^{\nu}) \tag{4}$$

We also extract the ship trajectories from the 2018 global ship movement data of Lloyd's List Intelligence, which lists the sequence of ports called by each ship. These trajectories and pairwise first-order risks are fed to the HON algorithm[20] to obtain the HON species flow. The HON algorithm is composed of two parts: Rule extraction and Network rewiring. The main purpose of Rule extraction is to identify the appropriate order of dependencies. The rule extraction steps are

1. Count subsequences of ship trajectory.
2. Given a source node, compute risk probability distribution of the next movement.
3. Given the source node and an extended source node before the current node, compute the new probability distribution of the next step, compare probability distributions before and after adding a previous stop. If there is a significant difference of two probability distributions, a second dependency is assumed at this point.
4. Repeat step (3), a third dependency may be assumed. If minimal support is not met or maximum order is achieved.

We empirically set the maximum order to 16. Based on the above procedure, the Rule extraction does not assign a fixed order but allows for variable order of dependencies. The data used is the ship trajectories and parameters in eqs 1−3. Network rewiring then converts the rules (identified orders of dependency) into a graph representation. It is important to note that in the HON network several nodes may correspond to the same port in the real-world. For example, all higher-order nodes A|B, A|B.C, and A|D.C.E corresponds to the port A. Given that, the number of nodes is an indicator of the number of higher-order patterns in the underlying data. The higher the number of nodes in the HON, the higher are the number of higher-order dependencies.[8] We encourage readers to refer to the work Saebi et al.[8] for more details.

Then we calculate the risk between two physical ports by averaging over all HON nodes that correspond to that pair of ports. Afterward, we normalize the edge weights by dividing all the edge weights by the maximum value in the network.

Finally, we get the cumulative risk for each port k by aggregating the spread risks over all incoming ports using eq 5:

$$p(\text{NISspread})_k = 1 - \Pi_i(1 - p(\text{NISspread})_{ik}) \tag{5}$$

Cluster Analysis of HAOP Spread Model. Cluster analysis provides a large-scale view of ship-borne species spread risk by identifying port groups within which ports are more connected and more likely to share species.[8] Such information can be useful for policymakers who wish to most effectively reduce global HAOP spread. *Infomap* is used to find clusters of nodes. *Infomap* identifies groups using a recursive random-walk method and optimizes the entropy corresponding to intracluster and interclusters. The random-walk method is suitable for species flow analysis because it is the most similar to the species flow pattern. It is important to note that we perform clustering on the higher-order network. As mentioned above, since multiple higher-order nodes may correspond to a single port, it is possible that a port belongs to multiple clusters.

Cost-Effectiveness Analysis. Policy effectiveness of HAOP risk reduction is described above. The global fleet compliance cost model is established separately for each technological alternative composed of two technological approaches: vessel- and port-based BWMS methods. The port-based BWMS discussed in the work is purpose-used barge-based treatment systems, designed, and examined to achieve California's Interim Goal.[27,40,41] The annual fleet compliance costs are composed of purchase, installation, and operating costs of BWMS (and barges if applicable), and treatment cost of BWMS (and tugs if applicable). Detailed descriptions of parameters and calculations can be found in the work of Wang and Corbett.[26] We update the model with ballast water discharge profile of 2018−2019 and adjust the number of barges needed at each port to incorporate the variation in ballast water treatment volumes and vessel arrival peaks (SI). We also estimate ballast water discharge with a random forest model, which performs better than the linear

Table 1. Relative HAOP Spread Risks of the Top 10 Riskiest Ports Under IMO Standards under Four Standards Scenarios: (1) No Standards, (2) In-Service Type-Approved BWMS, (3) IMO Concentration Standards Completely Met, And (4) Stricter California Standards Completely Met[a]

ranking	port	no standards (1)	in-service BWMS (2)	IMO standards (3)	stricter standards (4)
1	Singapore	1	0.934534	0.052499	0.002647
2	Hong Kong	0.711869	0.182962	0.005521	0.000340
3	Kashima	0.721975	0.172903	0.004862	0.000312
4	Algeciras	0.614709	0.142978	0.004118	0.000261
5	Gibraltar	0.901427	0.274569	0.003879	0.000261
6	Yosu	0.679988	0.153170	0.003841	0.000208
7	Las Palmas	0.561660	0.120302	0.003671	0.000248
8	Gwangyang	0.720563	0.137104	0.003521	0.000217
9	Shanghai	0.393780	0.092549	0.002762	0.000176
10	Pohang	0.468598	0.088633	0.002686	0.000120

[a] The difference between Columns (2) and (3) results from the fact that some in-service BWMS may fail to achieve the required standards.

regression model used before, as described in the HAOP spread risk model.

Under each policy scenario, we vary the number of high-risk ports to follow the IMO or stricter policy scenario. Since 4257 ports are related to the international shipping in 2018−2019 shipping traffic data (Lloyd's List Intelligence), we calculate and compare fleet compliance costs of different compliance strategies with our established models[26] for each of the 4257 policy cases.

Data. Shipping movement data are from Lloyd's List Intelligence, with ship travel information including origin and destination port, sail and arrival date, and vessel specifications. The data cover May 2018 to April 2019 with 1 425 157 individual voyages and 43 215 vessels. We use all shipping voyages in estimating invasion risks since every voyage with discharged ballast may contribute to species introduction. Then we exclude domestic voyages in the cost-effectiveness analysis since the ballast water regulations are for international-going vessels. Ballast water discharge records are from National Ballast Information Clearinghouse[42] of 2004−2019. This data totals 1.4 million records with vessel information. We keep 1.25 million records after removing those with missing information, or where ballast water discharge is higher than the capacity of ballast water tanks. Costs of BWMS are from literature[25,27] and the cleaning process can be found in our previous work.[26]

Environmental data are from the Global Ports Database[13] and the World Ocean Atlas.[43,44] We do not include the ports for which the environmental data are not available through these sources (such as Panama Canal, Dover Strait, Dardanelles, etc.). The temperature and salinity for 6695 ports were obtained, resulting in complete environmental data of 3006 of the 4257 ports included in LLI. The ecoregion data are from Marine Ecoregion of the World.[45]

■ RESULTS

Ballast Water Regulations Reduce Relative HAOP Spread Risks at Ports. Compared to no management, we show that the current BWM Convention reduces relative HAOP spread risks at ports and stricter ballast water management regulations further reduce their relative risks by a factor of 17 on average (Table 1). This finding is important because the real HAOP harms to the economy and ecosystem may be substantial even if *one* ship-borne species becomes invasive, as exemplified by the substantial economic and ecosystem harm caused by the zebra mussel, *Dreissena polymorpha*, in the Laurentian Great Lakes.[46−48] This analysis can also inform policymakers as to which ports are riskiest and allow them to consider imposing stricter regulation on such ports (e.g., Table 1 shows relative invasion risks for the top 10 ports with different policy efficacies).

Ballast Water Regulations Change Cluster Patterns of Ports' Relative HAOP Risks. Cluster analysis of the species-spread model under different scenarios reveals that stricter BWMS management simplifies high-order HAOP spread clusters and reduces intercluster HAOP spread risks (Figure 2, Table 2), which has important implications for both policy and HAOP surveillance strategies. The number of ports in multiple clusters, one measure of HON complexity, is very high under no BWMS scenario (Figure 2a), modest in the current BWMS scenario (Figure 2b) and lowest in the IMO and California 100% compliance scenarios (Figures 2c,d). This change can be attributed to the smaller numbers of HON nodes and HON edges under stricter different scenarios (SI Table S3) as more first-order and high-order risk connections drop to zero under structure management. A few ports, however, remain highly connected HON "hubs" under any scenario (e.g., Singapore, Hong Kong) and Shanghai actually becomes a relatively more important hub port under the strictest scenario, moving from the seventh most clusters under no policy to tied for the most clusters under the strictest scenario.

These results clearly show that concentration standards, and compliance rates with these standards, change not only relative HAOP spread risks but also the network configurations of these risk. These changes have important implications for policy and management. First, without any regulation, HAOP spread risk clusters are overlapping and globally connected, with many ports being in several risk clusters at once and risk cluster consisting of both geographically close and distant ports. The means that HAOP may spread easily around the world, which was the situation that motivated the IMO Convention. Our modeling show that current IMO standards compliance rates still enable quite a bit of HAOP spread compared to 100% compliance rates, while stricter California standards would reduce relative spread and network complexity modestly compare the current 100% IMO compliance (Figure 2, Table 2). This overall pattern suggests that increasing compliance rates, either to current IMO or stricter California standards, would be most effective a reducing current HAOP spread.

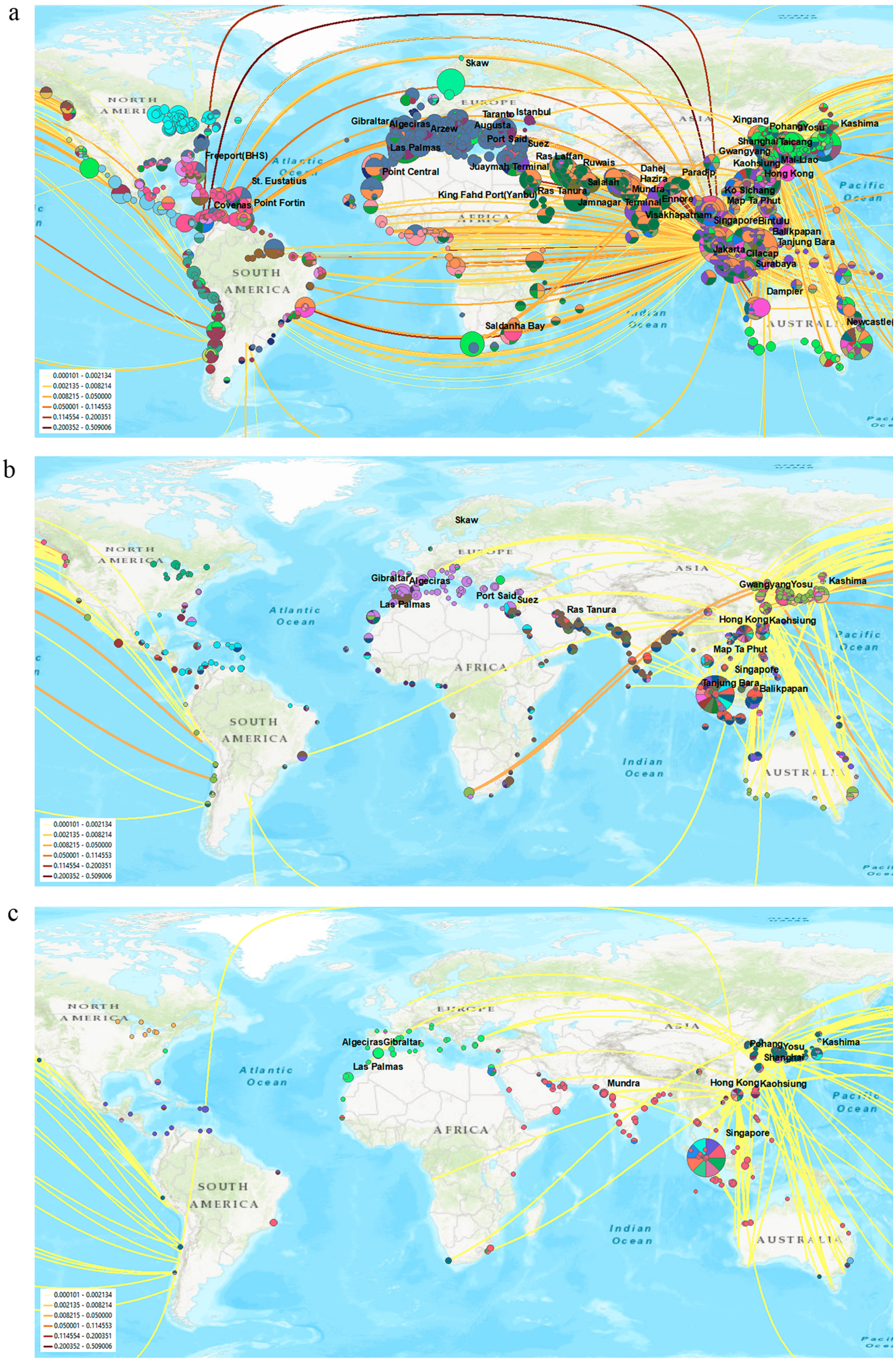


Figure 2. Main high-order species spread clusters (top 30) and risk connections (top 5000) under four scenarios: (a) no ballast water treatment, (b) efficacies of in-service BWMS under IMO standards, (c) efficacies perfectly achieving IMO standards globally, (d) achieve stricter (California's interim) standards globally. Lines represent aggregated HON spread risk between ports. High-risk connections are displayed darker, while low-risk connections are displayed lighter. Circle sizes show different relative risk of ports under the same regulation. Please note that port and connection risks are normalized within each particular treatment scenario so cannot be compared across scenarios. See SI Figure S2 for scenario risks normalized to the baseline "no policy" scenario.

Table 2. The Number of Clusters Linked by Selected High-Risk Ports

port	no treatment	in-service BWMS	IMO standards	stricter standards
Singapore	92	28	13	6
Hong Kong	24	15	11	5
Kashima	17	6	4	3
Algeciras	14	7	3	2
Yosu	16	7	5	4
Gwangyang	17	7	6	4
Shanghai	19	13	9	6
Mundra	12	5	4	3
Suez	20	8	3	2

Second, these results can identify clusters or ports for more target risk reduction efforts. For example, Figure 2 shows which ports are in the same cluster, and therefore have high HAOP spread risk between them, and could work together to reduce HAOP spread. Figure 2 also identifies "hub" ports, or ports connecting two or more clusters through the higher-order patterns. Such ports are vulnerable from more ports within different clusters and can serve at intercluster HAOP vectors. For example, Singapore has the highest invasion risk exposure under four treatment scenarios and connects many different clusters in the no-action conditions. Policymakers may choose more stringent regulations on such ports to reduce the port risks and break the intercluster HAOP spread.

Policy Scenario Cost-Effectiveness Analysis. Under current IMO BWM Convention standards, our cost analysis found that the current vessel-based approach follows the most cost-effective strategy. The BWM Convention of the IMO requires every international-going vessel to install a BWMS onboard, which is the case of Point A in Figure 3. At Point A, all 43 215 international-going vessels install BWMS onboard and the fleet cost is $3.3 billion/year (including capital, installation, operating costs of BWMS, and ballast water treatment costs). Current policy under BWM standards costs less ($9.7 billion/year) than port-based methods (Point B: $13 billion/year). The cost of barge-based method includes capital, installation (i.e., steel, paint, pipes, electrical, etc.), operating costs of BWMS and barged and tugs. Though a port-based BWMS can be shared by many vessels, the very high cost of port-based BWMS and the use of barges and tugs make the total cost higher than vessel-based BWMS. The intersection is where the port number is 350 and the fleet number is 36 004. When the first 350 ports or fewer are regulated under IMO regulation, the port-based methods cost less than vessel-based methods. This is because these ports tend to be large ports with many arrived vessels. Even though port-based BWMS costs much more than vessel-based BWMS, a large number of vessels make the vessel-based method more expensive. However, this is not enough to effectively protect water from species invasion.

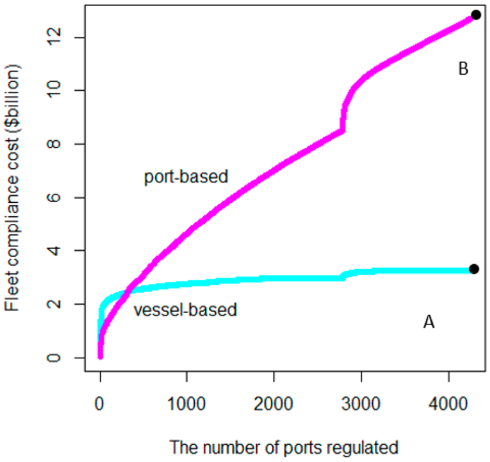


Figure 3. First x ports follow IMO regulation, other ports are not regulated. The purple line shows the costs of port-based treatment methods, that all regulated ports need to have BWMS at the port. The blue line represents the costs of vessel-based treatment methods, that all vessels are required to install BWMS onboard.

The findings under the stricter California standards scenario would be different. Figure 4 shows that the cost difference can be $20 Billion/year under two assumptions (the difference between the black/blue line and the green/purple line). Therefore, we can see from Figure 4 that barge-based treatment is more cost-effective than vessel-based treatment under stricter regulation.

In Figure 4, ports are ranked by risks after implementation of IMO regulations (followed by vessel arrivals) so that ports further requiring stricter regulations are selected. Global ports are divided into two groups, either adopt the IMO standards or adopt the stricter regulation. When x is 2, it means the top two ports are regulated by potential stricter standards and the other 4255 ports are regulated by IMO standards. Given the current IMO requirement of BWMS and installation status of the industry, we consider two different BWMS installation conditions for findings: no vessel has installed BWMS (Figure 4a) and all vessels have installed BWMS meeting IMO standards (Figure 4b).

In Figure 4a, if the IMO had adopted the stricter standards, then barge-based (purple/green curves) strategies are always cheaper than vessel-based options for stricter standards (black/blue curves). The purple and green lines intersect when the selected port number is 2882 and the annual fleet cost is $19 billion. Unless more than about 2882 of 4257 (67%, 2/third) of ports agree on stricter standards, regional action among ports, together with vessel-based treatment at other ports is more cost-effective. If more than 2882 ports agree on stricter standards, global barge-based implementation is less costly. The ultimate compliance strategy selection depends on the decision on which port or port sets are regulated by stricter standards, but one consistent conclusion is that the barge-based method is more cost-effective for those strictly regulated ports.

In Figure 4b, when all vessels have installed BWMS, vessels can use vessel-based BWMS when calling at ports regulated by IMO standards. For example, when x is 1, the green curve means that vessels use barge-based methods at Singapore and use installed onboard BWMS at other ports. The black curve is the vessel-based method, meaning the vessels calling at strictly regulated ports need to retrofit the vessel-based IMO-BWMS with stricter-BWMS. The barge-based method (green curve) is always less costly than the vessel-based method (black curve), no matter how many ports implement stricter regulations. This is because many vessels use the same barge-based BWMS at such high-risk ports, lowering the unit cost of centralized barge-based methods. Since vessels installed treatment before, the cost for vessel-based modeling would be increased modestly (compared to the black curve in Figure 4a).

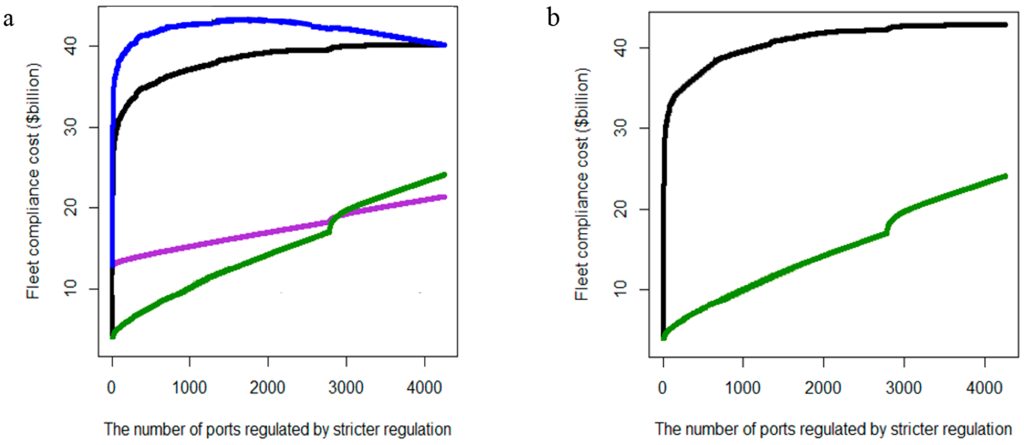


Figure 4. First x numbers of ports follow stricter regulation, other ports follow IMO regulation. a, four technological strategies when no vessel has ever installed BWMS (other combinations of the vessel- and barge-based BWMS strategies obviously more expensive are not included in the cost analysis). Blue: the vessel-based BWMS is used at strictly regulated ports, and the barge-based method is used at other ports. Black: the vessel-based method is used globally. Purple: the barge-based method is used globally. Green: the barge-based method is used at strictly regulated ports, and the vessel-based method is used at other ports. b, two compliance strategies left when all vessels have installed BWMS. Black: the vessel-based method is used globally. Green: the barge-based method is used globally.

Such implications are robust to the rank of ports and the "selected" ports regulated to current IMO or future stricter regulations. The least costly strategies remain the same when we modify the risk assessment model by excluding the ecoregion effect or when we vary shipping traffic. See details in SI Figures S3−S8.

We can also see higher costs by comparing Figure 4 and Figure 3, that the costs are higher when the standards are increased to the Californian suggestions. This is caused by more expensive capital, installation, operating, and treatment costs of stricter-BWMS, which are more effective to meet higher standards. The use of barges and tugs also increase the total costs.

■ DISCUSSION

The main findings of this research are as follows. (1) We find that stricter BWM policies can further reduce relative HAOP risks (by an order of 17 compared to the current BWM Convention) and alter higher-order species spread and clustering rates in a way that would make management of this complex network easier. (2) We identify hub ports that connect distinct clusters of ports within which species spread is high, and we show the barge-based technology is less costly for regulating hub ports. (3) The risk assessment together with technology-cost analysis shows that that the current policy of IMO standards is most cost-effectively achieved through BWMS on each ship, and that any additional risk reduction will be most cost-effectively achieved by port-based (or barge-based) technologies, particularly if these are strategically implemented at top ports within largest clusters. The latter results and suggest would require a geopolitical shift in global ballast water management away from vessels to ports.

While barge-based technologies to achieve stricter standards become more cost-effective for ports at greater risk of HAOPs, we confirm that vessel-based methods are more cost-effective to meet the standards set forth in the current BWM Convention. The results will stimulate technology innovation to move forward policymaking in global ballast water management. Also, the new strategy does not contradict current BWM Convention, since vessels do not need retrofit installed vessel-based treatment methods and will not be "grandfathered" at the expense of better protection from biological invasions.

More stringent environmental regulations being proposed and ratified and individual States adopting nationally stringent standards are not without precedent in the industry.[49] Also, Regulation C-1 of the BWM Convention explicitly acknowledges that a party of the BWM may propose more stringent amendments individually or together with other Parties, consistent with international law. In the legal and policy analysis toward potential invasion reduction from ballast water introduction, Firestone and Corbett (2005) think a more stringent discharge standard, presumably, could be included as an additional measure according to Section C.[50] Other than the BWM Convention, certain areas may decide to take action to regulate foreign-flag ships to address a particular concern regionally.[51] The Port and Coastal States can protect their jurisdictional waters under the United Nations Convention for the Law of the Sea (UNCLOS) or domestic laws.

Advantages of the IMO regulations include broader cooperation, more efficient global management, and possible cost allocation mechanisms. However, the BWM Convention depends upon fleet-regulation where IMO is the authority (through flag-state and port-state control) in regulating vessels, not ports. IMO Convention cannot require port-based (including barge-based) ballast water treatment methods. This suggests a science-based geopolitical shift in international environmental protection for shipborne invasive species. Cooperation among nations to reduce shipborne invasive species risk may for special areas designated by the IMO, by State or multistate authorities independent from the IMO, or by voluntary port applications. The key question is how nations come together.

The work identifies possible international agreement structures that most likely to work and identifies nations that are most likely to partner for shared benefits:

1 single port regulation. These ports will be cluster central ports, key risk partners in cluster risk, and ports connecting two or more clusters. For example, Port of Singapore connects 13 different clusters under the IMO regulation, forming a highway for species invasion

among different clusters. The stricter regulation on such ports not only improves biological safety at the port but also breaks down the interconnection of clusters and has a disproportionately positive role in reducing invasion risks globally.

2 bilateral/multilateral agreement. Ports belonging to the same cluster are more likely to become invasive to each other, such as ports in the Mediterranean Sea. They can work together to set stricter regulations to manage the biological invasion. Multilateral agreements can also include all economically feasible ports. Nations most likely to partner are identified in the cost-effectiveness analysis part. Refer to Data Availability for the highest risk ports identified by "group" and port−port bilateral risks; and

3 regional regulations. Figure 2(c) shows that the Great Lakes area, falling in the same cluster, has significantly higher invasion risk than other U.S. coastal areas under current Convention. This informs a stricter ballast water regulation toward the Great Lakes area. This is allowed by the Vessel Incidental Discharge Act of 2018 of the United States, stipulating that if proved appropriately, the Great Lakes basin can use different standards from the national one.

Risk results in our "no-treatment case" compare well with other research. We confirm that ship-borne species spread hotspots include East Asia and the Middle East. We identify current high-risk ports to include Singapore, Hong Kong, Kaohsiung, and Port Said, consistent with earlier work by Seebens et al.[11] Moreover, we confirm that Northeast Asia being the most significant species source for most regions, consistent with Sardain et al.[18] Importantly, our results under mitigation scenarios (e.g., Table 1) indicate that shipborne species spread risk can be reduced by a factor of 300 to 3000 by implementing stricter ballast treatment for high-risk ports, which may offset potential 3- to 20-fold risk increase due to global shipping traffic growth predicted by Sardain et al.[18] Taken together, the no-action and with-stricter-action scenarios may provide critical decision support, especially given the cost-effectiveness findings of feasible action by ports.

Like all vector-based species spread models, our risk model had to make several simplifying assumptions and has limitations. We recognize the coarseness of our ecoregion delineations for indigenous/nonindigenous connections does not adequately capture all species ranges, but we chose this as the best option for making generalizations globally. We also do not consider stepping-stone spread, whereby species may be spread indirectly between two ports but can share species through intermediary "stepping-stone" ports. Stepping-stone spread has been documented a few times in the literature,[52] but its importance globally remains unknown. Although we did not model stepping-stone spread explicitly due to high computational costs, we note that our clustering analysis does identify clusters of ports within which stepping-stone spread should be relatively high, and conclude that our main results would not change substantially should stepping-stone spread have been included. Finally, our model focuses on estimating ship-borne species spread (introduction + establishment) and not harm, while the BWM Convention focuses specifically on harmful aquatic organisms and pathogens. However, if we assume, like many do, that a small, constant subset of species will become harmful, then our risk model can be used for estimating nonindigenous HAOP risk. Our model's focus on ballast species spread also means that it does not consider other important vectors of species, such as ship fouling or aquaculture, nor does it consider secondary spread by recreational vessels.

We also made several assumptions regarding cost analysis due to uncertainties. We admit different vessels would install unique BWMS and the capital, installation, and operating costs for each BWMS would be different, while we do not distinguish BWMS and use the average costs in the cost analysis. However, as discussed in the sensitivity analysis of Wang and Corbett,[26] the cost-effectiveness analysis is very robust to the capital cost of BWMS, even when the capital is as low as $0.2 million and as high as $1.8 million. Also, the costs of barge-based methods are not market prices since such as barge-based BWMS are not available yet. However, the cost-effectiveness of such method shown in this work would motivate technology innovation toward such methods.[26] Our cost model here is based on 2018 shipping data and ballast water discharge profile, while our sensitivity analysis in the SI show that the cost-effectiveness results are robust to different patterns.

■ DATA AVAILABILITY

Ship movement data from Lloyd's List Intelligence are purchased and are not publicly available. Other data obtained are publicly available and cited. List of port risks, port clusters, and bilateral risks under different policy scenarios are available at https://github.com/msaebi1993/Scenario_SF_HON/tree/v.0.0/Data. The Code for generating higher-order network and synthetic data is available at https://github.com/msaebi1993/HON-ANOMALY

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.1c04009.

> Ballast water estimation with random forest model, policy efficacy estimation, plots of ports' relative risks, robustness analysis on cost-effectiveness, fleet compliance cost model update (PDF)

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The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript.

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

The work is based on the NSF Coastal SEES project (grant number 1748389). We thank NSF Coastal SEES for funding this work. We acknowledge David M. Lodge, Jeremy Firestone, Fabio Ballini, and Ronald A. Halim for suggestions on policy analysis and cost-effectiveness analysis.

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